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Frazil Ice Blockage of Intake Trash Racks

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Introduction

Operating water intakes in lakes and rivers in northern regions is complicated by the presence of ice. One of the most difficult problems is the accumulation of frazil ice on the intake trash rack, which can completely block the trash rack and rapidly and unexpectedly shut down the intake facility. In extreme cases the blockage can cause the intake trash rack to collapse. Blockages of intake trash racks occur sporadically, most often at night, in cold weather and always underwater. As a result, opportunities for observation and measurement are limited. This has lent frazil blockage an air of mystery that it does not deserve.

Contributing to the air of mystery is the lack of any universal cure for the problem of frazil ice accumulation on intake trash racks. While at many intakes there are no obvious techniques for preventing blockage, some successful techniques have been instituted at specific locations. Unfortunately, given the many uses and designs for intakes, and the wide range of hydraulic conditions at intakes, it has proven to be quite difficult to generalize these successful techniques.

Descriptions of frazil blockage can be found throughout the literature of cold regions engineering. People became aware of the problem as soon as they began to demand the uninterrupted use of rivers and lakes throughout the winter. The complete blockage of the water supply of the city of St. Petersburg, Russia, in 1914 by frazil ice is one early example. The writings of Murphy (1909),

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Barnes (1928) and others provide very good overall descriptions of frazil ice blockage.

This digest presents an overview of frazil ice blockage of intake trash racks for intake operators and designers. It describes the frazil ice blockage process, techniques (both successful and less so) for coping with frazil blockage, and guidelines for operating under frazil ice conditions. It synthesizes information from the literature, laboratory experiments, and the experience of the author. Broader and more general information on designing intakes for cold regions is available elsewhere (Logan 1974, Ashton 1988) as is information on frazil ice (Williams 1959, Michel 1971, Osterkamp 1978, Martin 1981, Daly 1984, Ashton 1986).

The blockage process

Frazil ice accumulates on intake trash racks under conditions that make direct observation very difficult. As yet, there have been no quantitative measurements made while frazil ice was accumulating on an intake trash rack outside of a laboratory. Our understanding of the accumulation process comes from photos of river intake trash racks raised after becoming completely blocked, descriptions from intake operators, and experiments conducted at CRREL.



Rivers

The accumulation process starts when the water entering the intake becomes supercooled, that is, when the water is below its freezing temperature. The degree of supercooling may be very small (less than 0.01°C) and nearly impossible to detect without laboratory-grade equipment. Supercooling requires a large heat loss rate from the river that is always associated with low air temperatures (about -6°C or lower), open water and most often, clear nights. The association of frazil production and open water is so strong that it can be said quite confidently that trash racks will be blocked by frazil only before a stable ice cover has formed, after the ice cover has broken up, or where a stable ice cover cannot form.

The water will supercool first at the surface, and in rivers the highly turbulent flow will mix the supercooled water quickly through the entire depth. Carried along with the supercooled water will be small crystals of ice—frazil ice—which, because of their small size, will have little effective buoyancy and will be easily carried to the bottom of the river. The first few crystals enter at the water's surface, and through a process known as secondary nucleation, the number of crystals quickly increases. The concentration of crystals in rivers has not been measured, but estimates are in the range of 1 million per cubic meter (approximately 30,000 per cubic foot). Because they are in supercooled water, the crystals will be growing in size and will stick to any object they contact—including

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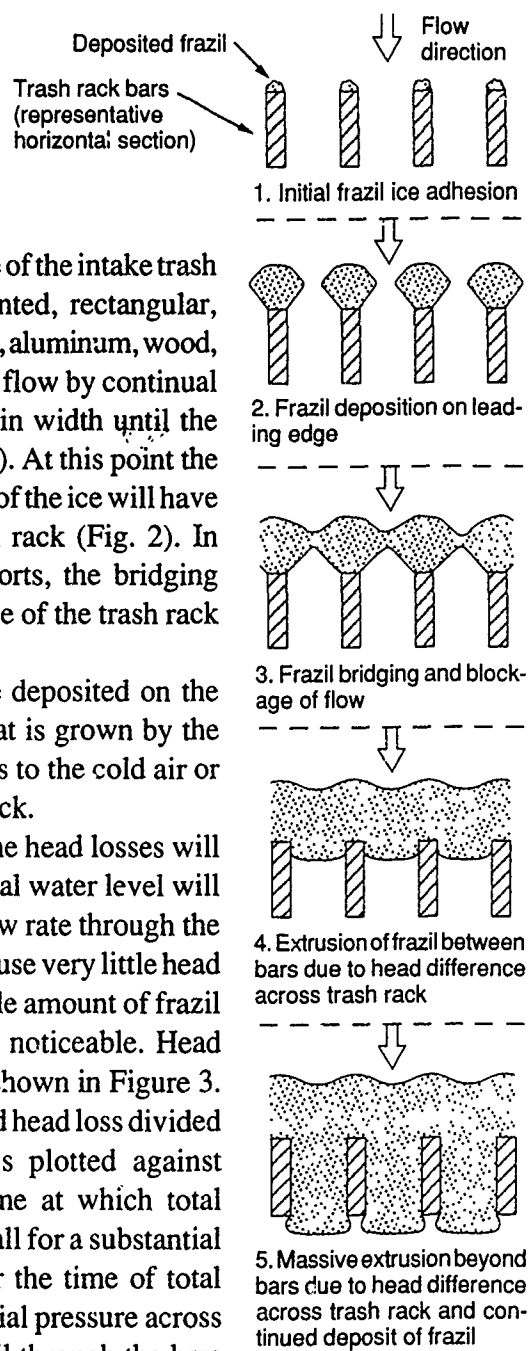
trash racks—as long as these objects are at a temperature below freezing. Given the effective heat transfer rates provided by flowing water, any object in the water that is not heated will quickly be at the temperature of the supercooled water and will accumulate frazil.

The frazil will collect first on the upstream face of the intake trash bars, regardless of the shape of the bars—pointed, rectangular, rounded, streamlined, etc.—or the material—steel, aluminum, wood, plastic, etc. The accumulation will grow into the flow by continual deposition, extending upstream and increasing in width until the space between adjacent bars is “bridged” (Fig. 1). At this point the trash rack will be effectively blocked. Almost all of the ice will have accumulated on the upstream side of the trash rack (Fig. 2). In laboratory experiments, and in some field reports, the bridging process is observed to occur first at the water line of the trash rack and then extend downward.

Calculations indicate that the quantity of ice deposited on the trash rack will far exceed the quantity of ice that is grown by the transfer of latent heat through the trash rack bars to the cold air or to the supercooled water flowing through the rack.

As the frazil accumulates on the trash rack, the head losses will increase. That is, a greater and greater differential water level will be required across the rack to drive the same flow rate through the trash rack. Because trash racks are designed to cause very little head loss under normal flow conditions, a considerable amount of frazil can accumulate before this head loss becomes noticeable. Head losses measured in laboratory experiments are shown in Figure 3. Here the nondimensional head loss (the measured head loss divided by the head loss of the rack without ice) is plotted against nondimensional time (time divided by the time at which total blockage occurs). The head loss is relatively small for a substantial period of time but increases quite rapidly near the time of total blockage. As the head loss mounts, the differential pressure across the rack will tend to push the accumulated frazil through the bars and may even extrude the accumulated frazil completely through the trash rack (Fig. 1 and 4). Once the frazil has been extruded between the bars, it can adhere to a much larger area of the bars. As a result the accumulated frazil can withstand quite high differential pressures, equal to many feet of water.

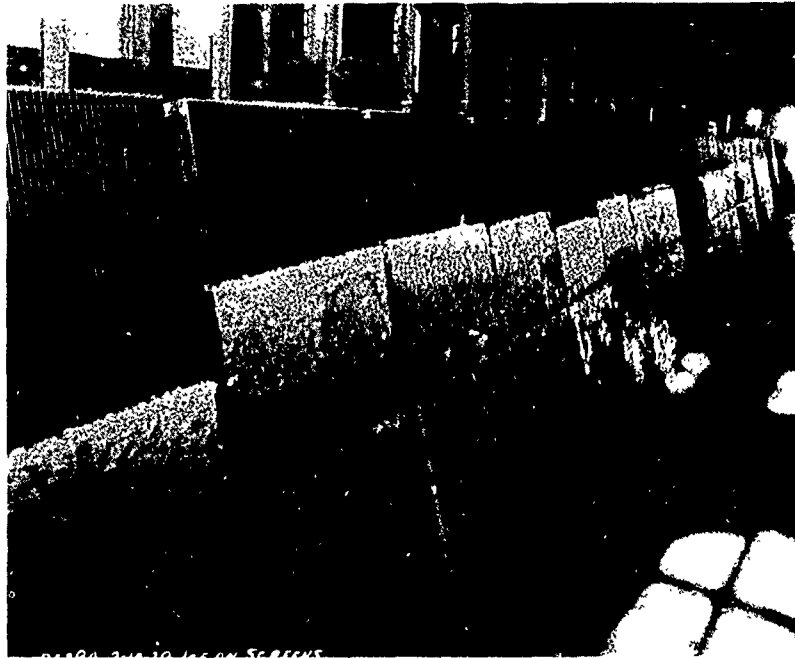
The process of blockage of intake trash racks in lakes has never been directly observed because of the racks' remote and often deep locations. As with river intakes, blockages of lake intake trash racks



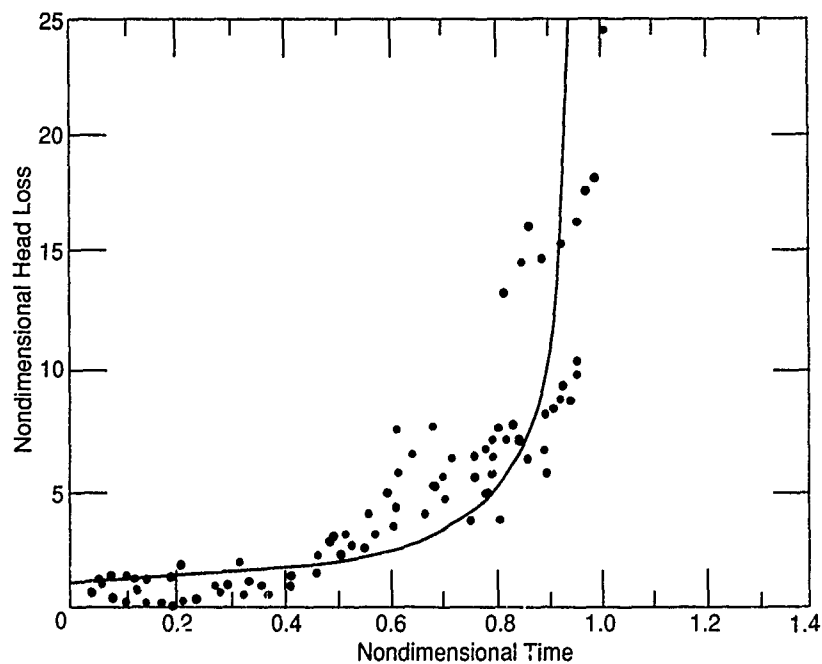
1. Pattern of frazil ice accumulation on intake trash rack bars.

Lakes

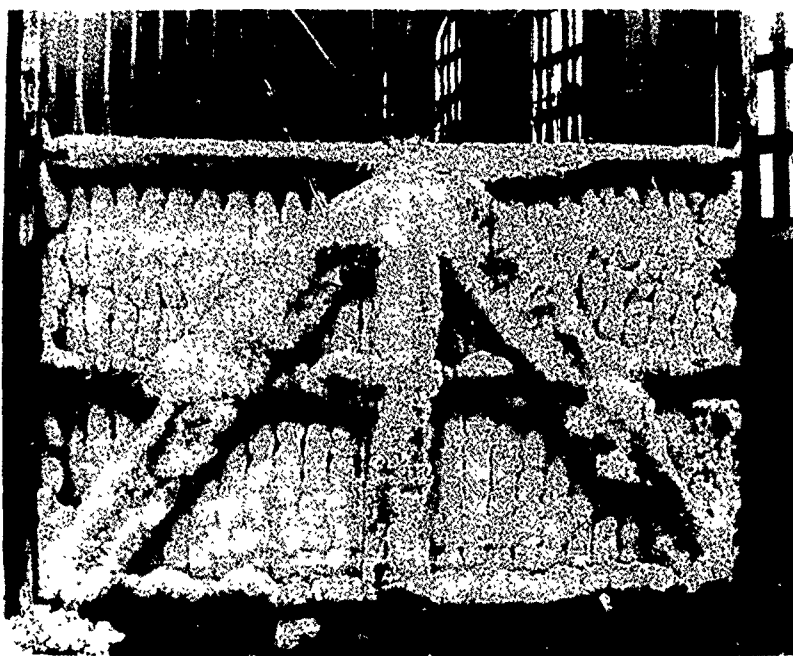
2. Accumulated frazil
on trash racks raised
from the water. (Photo
courtesy of Pennsylv-
ania Power & Light
Company.)



3. Head loss through a
trash rack during frazil
ice accumulation in
laboratory tests.



are associated with open water, low temperatures and clear nights. They are often also associated with strong winds, which increase the rate of heat loss at the water surface and may provide the turbulence that can mix the supercooled water to the depth of the intake. The intake flow can also entrain the supercooled water if it is high enough. The depth at which a lake intake will be safe from frazil blockage cannot be estimated simply, and it probably depends on



4. Back side of an intake trash rack raised from the water, showing massive extrusions of frazil ice through the rack bars. (Photo courtesy of Pennsylvania Power & Light Company.)

many factors, such as the fetch length, bottom topography, intake depth and intake flow rate. Blockages have been reported at intakes 20 m deep and much deeper.

The blockage of lake intake trash racks probably occurs in much the same way as river intakes. However, inspections of blocked lake intakes by divers suggest that the individual crystal size is larger at lake intakes than at river intakes. The reasons for this are not entirely clear, but it may result from a lower concentration of crystals in suspension because of the lower levels of turbulence in lakes. This means that the accumulated crystals may actually grow due to the release of latent heat allowed by the constant intake of supercooled water. This is in contrast to the river intakes, where the deposition of frazil crystals is by far the most significant source of ice.

Lake intakes are most often connected with a wet well from which water is pumped. As the intake trash rack becomes blocked, the wet well may be drawn down, and the differential pressure across the trash rack will increase. This differential pressure has been known to cause intakes to collapse. Close monitoring of the water level in the wet well may help in detecting blockage of the trash rack by frazil ice.

Many techniques have been tried to keep intake trash racks free from frazil ice. In the next few pages are listed some of the basic techniques that have been tried (not always successfully) or are frequently suggested.

Coping with frazil blockage

*Suppressing
frazil production*

An intact, stable ice cover will always prevent the production of the frazil ice by "insulating" the water surface and preventing large heat loss rates responsible for supercooled water. If an ice cover can be successfully created and kept in place over a sufficient area of the river or lake in which the intake is located, frazil blockage probably can be completely avoided. There is no ready "rule of thumb" as to what is a sufficient area of the water surface that must be covered by ice. Supercooled water traveling beneath an ice cover will gradually be warmed to the freezing temperature by the latent heat released by the growing frazil crystals and the surface ice cover and by viscous dissipation in the flow. While Ashton (1988) suggested that a cover length equal to 10 minutes of travel time may be adequate to warm the water sufficiently, supercooled water has been measured several kilometers downstream from the head of an ice cover and with travel times as long as 1½ to 3 hours on large rivers. The actual length required will vary widely, depending on the hydraulic conditions in the river. The techniques for creating and maintaining stable ice covers are described well elsewhere (U.S. Army Corps of Engineers 1982, Ashton 1986).

Using heat

The use of heat can be a very successful way to prevent frazil from adhering to intake trash racks. It is not effective or efficient to use heat to melt ice once it has accumulated on the trash rack. Rather, the heat should be used to prevent adhesion to the trash rack by warming the incoming water so that it is no longer supercooled or by warming the trash rack bars so that they are above the freezing temperature. The most attractive source of heat is the warm water that is often a byproduct at facilities that use intakes, such as the cooling water at power generation plants. The warm water is often dumped back into the river downstream of the intake and is essentially thrown away! By redirecting a portion of this waste heat to the intake, frazil blockage can be avoided. At small intakes, ground water may also be an adequate heat source. Enough warm water should be redirected to the intake to raise the entire intake flow temperature 0.1–0.2°C. If it is assumed that all the warm water will be drawn into the intake, the amount of water Q_D required is

$$Q_D = Q_T \left(\frac{T_R}{T_D} \right)$$

where Q_T = total intake flow rate

T_R = temperature rise above freezing required

T_D = temperature above freezing of the warm water to be delivered to the intake.

The warm water should be introduced immediately upstream of the intake trash rack, and it should be well mixed in the intake flow. Mixing the warm water with the intake flow can require the use of "sprayers" or diffusers, but complicated designs for these devices are not usually warranted.

Another means of using heat to prevent frazil blockage is to heat the trash rack bars directly. If the bar temperatures can be kept above the freezing temperature, frazil will not adhere. The amount of heat supplied must be sufficient to offset the heat transfer to the flowing, supercooled water. Standard heat transfer relationships that relate the heat transfer to the bar shape and water velocity are available to guide designers (see, for example, Logan 1974); the degree of safety provided in the design is the temperature difference maintained between the trash rack bars and the supercooled water temperature. As a minimum the bars should be maintained at 0.1°C , but it is advisable that bar designs include the capability to maintain the bars at $1.0\text{--}1.5^{\circ}\text{C}$ during high frazil concentration events.

There is no simple means of supplying heat to the trash rack bars. Hollow bars, through which steam or warm water is pumped, have been used successfully. However, these systems seem to suffer from many operational problems. Incorporating resistance heaters in the trash rack bars has also been used successfully. In Sweden and other locations, energy is delivered to the trash rack bars by direct electrical connection. This often requires that the trash racks be redesigned, and safety is then a consideration.

Constructing heated enclosures over intakes is sometimes suggested, especially where large portions of the trash rack are exposed to air. However, heated enclosures by themselves cannot prevent frazil ice accumulation. The heat gain to the trash rack from the warm air developed within the enclosure will be balanced by the heat loss to the flowing water at a very small depth. The depth will depend largely on the bar size and the flow velocity but will probably be no more than several bar diameters below the surface. Below this depth, frazil will accumulate as described above. While heated enclosures will not prevent frazil accumulation, people working near the rack (raking, for instance) will appreciate the warmth.

Probably the most widespread method of dealing with frazil accumulation of intake trash racks is to use rakes to remove the ice. As seen earlier, before the development of large differential pressures across a trash rack, the accumulation of frazil ice will be largely on the upstream side of the racks. During this time it is relatively easy to remove by raking. Manual raking is undoubtedly

*Mechanical
removal*

the single most widely used technique for dealing with frazil—"a strong back in a warm coat" can effectively clear large areas of racks covered with frazil ice. The cost of labor, the cold and wet working conditions, and the late night hours, however, combine to discourage this approach.

An alternative to manual raking is to use mechanical rakes. There are a number of manufacturers of mechanical rakes with a corresponding range of sophistication, from relatively simple, manually operated power rakes, to rakes using the best of robotics. Problems that can arise in operating mechanical rakes in very cold weather should not be ignored. The rake mechanisms inevitably move from completely submerged conditions to the cold air, leading to the formation of hard ice and resultant mechanical problems. Therefore, the usefulness of a mechanical rake for removing frazil in cold weather must be carefully evaluated.

The use of high-flow air bubblers and water jets is sometimes suggested as a means of removing frazil accumulations on intake trash racks. At present the use of high-flow air bubblers remains strictly experimental and should be approached as such. Water jets have been used successfully to remove frazil ice accumulations inside large conduits and may be effective for use with trash racks.

Back flushing

Back flushing is a technique to reverse the differential pressure across the trash rack. During back flushing, a higher pressure is created on the back side of the racks, and the flow through the rack is reversed. If the accumulation of frazil is largely on the upstream side of the rack (as in Fig. 1c), then it is likely that back flushing will be successful. This means that back flushing must be done as soon as possible during the accumulation process, before large differential pressures occur and the accumulated ice is extruded between the bars. If the accumulation has been extruded between the trash rack bars (as in Fig. 1d and 1c), then it is much less likely that the back flushing process will be successful.

Back flushing is accomplished by any means that the intake operators may have for increasing the pressure on the back side of the trash rack. Most often, back flushing is tried at intakes connected to wet wells, where water is allowed to flow from elevated tanks or stand pipes or is pumped into the wet well. Back flushing should be repeated frequently as long as frazil ice conditions persist.

Coatings and alternative trash rack materials

Almost all trash racks are made of metal—the vast majority of steel, a very few of aluminum. Steel in water quickly rusts, and the adhesion strength between ice and rusted steel is extremely high. Trash rack coatings will reduce the ice adhesion strength and can

extend the time to total blockage, but coatings by themselves will not prevent frazil blockage. Examples of coatings are two-part epoxies or heavy-duty marine-type paint. Coatings must be applied only after careful preparation of the racks, which at a minimum involves a thorough cleaning, usually by sand blasting. While coatings cannot prevent blockage, they will increase the ease of removal of frazil ice (such as by raking, for example).

Alternative trash rack materials—that is, nonmetals such as plastics, fiberglass, graphite or other material—must be carefully selected to provide the strength and durability required. Materials such as these will, like coatings, have a lower ice adhesion strength than steel, but “no material is known to which ice will not adhere” (Ashton 1986). As a result, using alternative materials for trash rack construction is not in itself a guarantee against ice blockage, but again, like coatings, they will allow frazil ice to be removed more easily.

Vibration of trash racks has been shown to be effective in removing frazil ice accumulations in laboratory tests (Mussalli et al. 1987). In these tests a minimum vibration acceleration of 15 g was needed to shed accumulated frazil ice from the model trash racks. Under prototype conditions, enough energy must be supplied to remove ice but not to shake the trash rack apart. The natural flexibility of trash racks may make effective vibration difficult, and it also may make it difficult to vibrate an entire rack uniformly from one application point. Electric- or air-powered vibrators are used for many applications and are commercially available, but they will probably need to be modified for underwater use. At present the use of vibrators must be considered an experimental technique.

Vibration

Dynamite is sometimes used to remove accumulations of frazil from intake trash racks under extreme conditions. Blasting is effective, probably because of the vibrations set up in the trash rack combined with the pressure wave of the explosion. The first problem with blasting is to determine the correct size of the charge. It must be large enough to remove the ice but not so large as to damage the rack. Additional problems arise from environmental concerns, safety considerations and the complaints of nearby residents. Because of these problems the use of dynamite cannot be recommended.

Blasting

Removing the trash racks is an obvious solution and one that is sometimes used. The trash racks should be removed only after carefully weighing the problems caused by the frazil accumulation

Removal of trash racks

against the damage that may be caused by not having the trash racks in place. This type of evaluation can only be done after many years of experience at a particular site and is not a step to be taken lightly.

**Operating
under frazil
conditions**

Maintaining adequate intake flow under frazil ice conditions can be very difficult. Given below are guidelines for intake operators who must maintain an uninterrupted supply of water and who face frazil ice conditions and frazil accumulation on the intake trash racks.

1. Monitor the water temperature, air temperature and surface ice cover extent to develop associations between these conditions and the formation of frazil ice. Almost all intake operators monitor these conditions as a routine matter and learn to anticipate the conditions under which frazil ice occurs. When the water temperature is close to freezing and no surface ice cover exists, forecasts of low air temperatures and clear nights should alert operators to the possibility of frazil ice.

2. Continuously monitor the degree of blockage on the intake trash rack. This can be done by measuring the differential pressure or water level across the trash rack or by visual inspection. At intakes that pump from a wet well, the water level difference between the wet well and the water level in the body of water in which the intake is located should be monitored. The degree of blockage will be indicated by the extent that the water level differential exceeds that found under normal operating conditions (caused by head losses in the intake structure and the intake piping systems). Continuous readouts of the instruments used to monitor these conditions should be available to the facility operators, and alarm conditions should be established. The chief benefit of this monitoring is to allow the operators to determine quickly and unambiguously the degree to which the trash racks are blocked, so that the appropriate measures can be taken.

3. Frazil ice accumulation can be minimized to some extent, although not eliminated altogether, through proper design of the intake trash racks. By having the maximum space between the trash rack bars and by using the thinnest bars possible with the minimum of supports consistent with strength and vibration considerations, the length of time until the intake is totally blocked can be extended. The ability of the rack to withstand the differential pressure under blocked conditions should also be carefully considered. A conservative approach is to design the rack to withstand the entire head of water possible on the upstream side of the rack. Some river intake trash racks are designed to this standard. This standard may not be practical for all intakes. The design should then reflect the maxi-

imum differential pressure the intake trash rack may experience given the monitoring program established as described above.

4. Develop plans for an orderly shutdown of the facility should the intake trash rack become blocked by frazil.

5. Take an active approach to dealing with frazil ice by using one of the techniques described in the previous section. If possible, actively manage the ice cover in the area of the intake to establish a stable ice cover as soon as possible in the winter season and to maintain it as long as possible. If there is a source of heat available, use it! Coat a section of your trash rack and then observe the results—is the ability to rake improved? If coatings are an improvement, consider coating the entire trash rack at your site.

6. Keep detailed logs of the water temperature, weather conditions and ice conditions throughout the winter to determine the specific conditions at which frazil ice blockage occurs. Determine simple alarm conditions based on these observations and make sure that the operating personnel are aware of them. Operating personnel have often developed keen insights into frazil problems from hard experience. Gather information from these people and make sure that it is not lost due to retirement or personnel changes.

Frazil ice blockage is a difficult and serious problem. By taking active measures, by compiling information about when frazil blockage occurs, and by anticipating its occurrence, the problems caused by frazil blockage can be minimized.

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Acknowledgments

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